Design of Experimental Studies by the Taguchi Method

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Abstract: *The research aims to analyze in depth the process of designing experiments by applying the Taguchi method, an approach recognized for its efficiency in optimizing experimental studies. Within this approach, the fundamental steps have been identified and detailed, as well as the specific steps to be followed according to the principles of this method. Thus, a detailed plan for the organization of the experiments was developed, which included the validation of the factors with significant influence on the results, the precise definition of the study parameters essential for the research objectives and the determination of the orthogonal matrix of the experiments, a key tool in ensuring a systematic and efficient approach. Based on these elements, the optimal number of experiments needed to conduct experimental research was determined.*

Keywords: *Taguchi method, design of experiments, orthogonal matrix, factor validation*.

1 INTRODUCTION

Scientific research is a process that combines fundamental and applied investigations, including scientific exploration, technological development, concrete research results and associated services as essential elements. It is currently the main method of analyzing modern progress, being structured on two major directions: theoretical and experimental research.

The objective of this study is to establish the necessary number of experimental tests for research based on practical experiments. It is initially intended to process five distinct types of surfaces, using a single type of material. The processing will be carried out with two cutter variants, and the cutting regimes will include three variable parameters, the others being kept constant.

Experiment planning, also known as statistical design of experiments, consists of a structured series of repeated experimental tests. These are achieved by the controlled adjustment of one or more initial factors (input parameters), with the aim of obtaining new useful information for the economic validation of a model.

This approach is based on the Box-Wilson experimental strategy, which uses a factorial design. Its peculiarity lies in the simultaneous modification of all the factors involved in each experimental test. Thus, the impact of each factor on the results (response function) is evaluated based on all the experiments performed. In addition, the initial model of the experimental design, usually a linear one, provides clues as to the direction in which the optimal value of the response function lies, according to references [1], [2].

Classical experimental design processes are often complex, expensive and difficult to apply. As the number of parameters of a process increases, it becomes necessary to carry out a large volume of experiments. To overcome this limitation, the Taguchi method uses an innovative design based on orthogonal networks, which allows the full exploration of the parameter space with a reduced number of tests.

The Taguchi method is widely applied in the engineering field and involves the development of an experimental plan meant to generate data in a controlled way, providing valuable information about the dynamics of a specific process [3], [4]. Its main advantage lies in reducing the effort required for experiments, saving time, reducing costs and quickly identifying factors with a significant impact.

This method focuses on determining the optimal values of controllable factors, which can be adjusted to minimize the sensitivity of the investigated process to variations in uncontrollable factors. Taguchi called this type of challenge "robust parameter design." The concept of robustness describes products or processes capable of maintaining a low variation in characteristics, even in the presence of disturbances caused by fluctuating factors.

The objective of the design of experimental parameters is to identify the levels of controllable variables that ensure a product or process resistant to variations. These controllable variables can be quantitative or qualitative in nature and are frequently influenced by factors such as environmental conditions (e.g. humidity or temperature during production), characteristics of raw materials or other properties of semi-finished products.

Taguchi methods, which integrate the principles of experimental design with the theory of the quality loss function, have been used to create robust models of products and processes, while also helping to solve problems related to production control [5, 6, 7, 8, 9].

The Taguchi technique is a methodological approach designed to establish the optimal configuration of controllable factors, so that the product or process becomes less vulnerable to the influence of disturbing factors [10].

Due to its versatility, Taguchi methods are widely used in technical engineering, being applicable in areas such as optimization, experimental design, sensitivity analysis, parameter estimation or model behavior prediction.

2 STAGES OF THE TAGUCHI PROCEDURE

The Taguchi optimization technique is a distinct and effective approach that differs from conventional optimization methods. While traditional experimental design methods can be complicated and time-consuming, the Taguchi methodology stands out for its accessibility and simplicity of use.

The procedure applied for optimization by the Taguchi method in this study is illustrated in Figure 1.

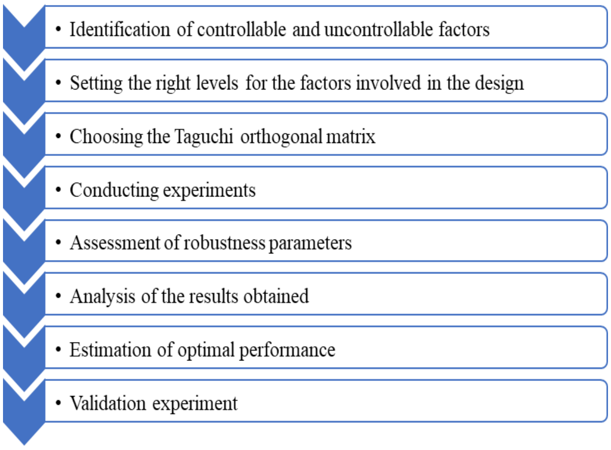

Fig. 1. Taguchi Design Procedure [3-4]

Taguchi methods are widely used in the field of technical engineering, having diverse applications, such as process optimization, experimental design, sensitivity analysis, parameter estimation and model behavior prediction, among others.

The central concept of the robust design proposed by Taguchi, which differentiates it from traditional experimental approaches, lies in its ability to simultaneously model both the mean value and the variability of the results.

For the implementation of the Taguchi method in the planning of experiments, it is necessary to follow six distinct stages:

Step 1. Gathering all pre-existing information, also taking into account the hypotheses that can be formulated;

Step 2. Clearly define the objective, including the number of factors analysed, take into account or ignore the interactions between them, and determine whether it is sufficient to identify linear influences alone;

Step 3. Establishing the series of experiments necessary to achieve the objective defined in step 2, based on the initial knowledge specified in step 1;

Step 4. Conducting planned experiments;

Step 5. Statistical analysis of the results, which includes the evaluation of variance, the elaboration of a dependency equation and optimization;

Step 6. Interpreting and confirming the results obtained through experimentation.

Using the Taguchi method is quite simple, but it requires a solid theoretical understanding, which can be acquired through individual study and group collaboration. This method allows you to achieve fast and impressive results with minimal effort, while generating significant economic benefits.

3 RESEARCH PLANNING

Research planning is carried out on two main axes: on the one hand, the researcher relies on his previous experience and knowledge, including the literature and the objectives of the project – i.e. on the questions to be answered. Planning, on the other hand, is creating a bridge between what is already known and what is yet to be discovered.

This process involves setting priorities and tailoring them to research questions, as well as evaluating each other. The revision of the plan from the perspective of feasibility allows the adjustment of the objectives and methods, as well as the optimization of the allocation of the time necessary to carry out the research.

The main purpose of planning the research activity is to obtain the desired results in conditions of maximum efficiency. Therefore, the determination of the volume of measurements or samples will be made based on the following criteria:

- Machining precision;
- The time required for processing;
- Tool wear standard.

An insufficient number of measurements can compromise the accuracy of the results, while an excessive volume can overload the research program. Therefore, data must be systematically correlated and analysed to ensure valid and relevant conclusions.

The design of the experiment is based on the configuration of the test stand shown in Figure 2, which establishes the methodological framework of the investigation.

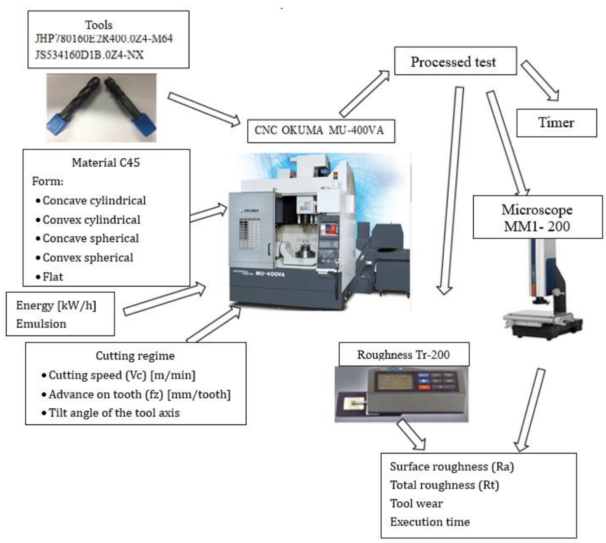

Fig. 2. Diagram of the experimental stand

The experimental stand allows the fulfillment of the essential requirements for achieving the proposed objectives, providing relevant experimental data. These data make it possible to analyze the influence of process parameters – such as cutting speed, feed per tooth and inclination angle – on surface roughness in milling complex surfaces with toroidal milling cutters.

4 VALIDATION OF FACTORS AND DEFINITION OF STUDY PARAMETERS

The Taguchi method, being designed for the efficient planning of experiments, requires the implementation of a structured methodology that includes the following essential steps:

• Determination of influencing factors - Identification of all significant variables that affect the cutting process in the case of toroidal milling

• Selection of study parameters - Definition of operational parameters relevant to the investigation

• Establishing the ranges of variation - Setting the optimal levels for each analyzed parameter

• Design of experiments - Parametric organization in orthogonal matrix according to Taguchi.

• Execution of tests - Conducting experiments based on the established plan and data processing - Statistical analysis and interpretation of the results.

All these stages lead to a good management of the experiments so that at the end of their completion, the data obtained transmit the most practical, efficient and real information.

According to the Taguchi methodology, the initial stage in the experimental design of the milling process consists in the systematic identification of influencing factors. This fundamental phase serves as a starting point for the entire experimental structure, within the experiments to be carried out, the main factors of interest are:

• Cutting speed- vc [mm/min];
• Advance on tooth fz [mm/tooth];
• The angle of inclination of the tool axis.

Starting from the cutting regimes suggested by the manufacturer to ensure an efficient development of the experimental plan, three levels will be considered, corresponding to the minimum, average and maximum values of each adjustment factor for each cutter, as shown in the tables below.

Table 1. Control parameters and level values of the toroidal cutter

Parameter Name	***Minimum value***	***Average value***	***Maximum value***
Cutting speed	80 [m/min]	170 [m/min]	210 [m/min]
Advance on tooth	0,11 [mm/tooth]	0,15 [mm/tooth]	0,19 [mm/tooth]
Angle of inclination	15°	35°	55°

Table 2. Control parameters and level values for the spherical cutter

Parameter Name	***Minimum value***	***Average value***	***Maximum value***
Cutting speed	280 [m/min]	370 [m/min]	430 [m/min]
Advance on tooth	0,05 [mm/tooth]	0,09 [mm/tooth]	0,13 [mm/tooth]
Angle of inclination	15°	35°	55°

5 DETERMINING THE EXPERIENCE MATRIX

Starting from the conditions necessary for the development of a design of experiments, orthogonality is the fundamental requirement in calculating the effects of a factor independent of the other factors. The goal is to perform as few experiments as possible, using the Taguchi method, by combining the factors established with the help of orthogonal tables, to determine a matrix of experiments. In this context, it is essential to establish the total number of degrees of freedom.

To calculate degrees of freedom, the matrix of experiences must have a number of degrees of freedom at least equal to the total number of degrees of freedom required. Thus, considering the three factors established at three levels, the degrees of freedom are associated with: 3x3 = 9. Considering the three parameters analyzed, 3 interactions will be made between them, i.e. 3x3x3 = 27.

Therefore, the minimum number of degrees of freedom must be 27, which requires that the matrix contain at least 27 attempts. Thus, for the 3 parameters analyzed, an appropriate experience matrix is formed.

Taking into account the Taguchi method, the closest matrix is L27 (33) where L27 signifies the 27 lines of the matrix equivalent to the experimental plan containing 27 attempts, and 33 represents the 3 columns with 3 digits for 3 levels.

$$\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 2 \\ 1 & 1 & 3 \\ 1 & 2 & 1 \\ 1 & 2 & 2 \\ 1 & 2 & 3 \\ 1 & 3 & 1 \\ 1 & 3 & 2 \\ 1 & 3 & 3 \\ 2 & 1 & 1 \\ 2 & 1 & 2 \\ 2 & 1 & 3 \\ 2 & 2 & 1 \\ 2 & 2 & 2 \\ 2 & 2 & 3 \\ 2 & 3 & 1 \\ 2 & 3 & 2 \\ 2 & 3 & 3 \\ 3 & 1 & 1 \\ 3 & 1 & 2 \\ 3 & 1 & 3 \\ 3 & 2 & 1 \\ 3 & 2 & 2 \\ 3 & 2 & 3 \\ 3 & 3 & 1 \\ 3 & 3 & 2 \\ 3 & 3 & 3 \end{pmatrix}$$

Fig. 3. Orthogonal matrix in accordance with the Taguchi method for choosing the values of each experiment

Since the same orthogonal correspondence matrix is used according to the Taguchi method, the experiment matrix L27 (33) remains constant in both cases for both toroidal and spherical milling experiments.

According to the orthogonal matrix, the 27 tests for each type of cutter and for each surface are considered optimal variants of the combinations of the values of the cutting regime parameters, with the aim of identifying the most favorable level of each factor in order to reduce the dispersion of the cutting process and obtain a superior surface quality. At the same time, the productivity level of the two types of cutters will be observed. Tables 3 and 4 present the values of the parameters corresponding to each test, according to the Taguchi experiment plan.

Table 3. Parameter values for each toroidal cutter test

Experiment Number	Cutting speed [m/min]	Angle of inclination [°]	The advance on the tooth [mm/dinte]
1	80	15°	0,11
2	80	15°	0,15
3	80	15°	0,19
4	80	35°	0,11
5	80	35°	0,15
6	80	35°	0,19
7	80	55°	0,11
8	80	55°	0,15
9	80	55°	0,19
10	170	15°	0,11
11	170	15°	0,15
12	170	15°	0,19
13	170	35°	0,11
14	170	35°	0,15
15	170	35°	0,19
16	170	55°	0,11
17	170	55°	0,15
18	170	55°	0,19
19	210	15°	0,11
20	210	15°	0,15
21	210	15°	0,19
22	210	35°	0,11
23	210	35°	0,15
24	210	35°	0,19
25	210	55°	0,11
26	210	55°	0,15
27	210	55°	0,19

Table 4. Parameter values for each ball milling machine test

Experiment Number	Cutting speed [m/min]	Angle of inclination [°]	The advance on the tooth [mm/dinte]
1	280	15°	0,05
2	280	15°	0,09
3	280	15°	0,13
4	280	35°	0,05
5	280	35°	0,09
6	280	35°	0,13
7	280	55°	0,05
8	280	55°	0,09
9	280	55°	0,13
10	370	15°	0,05
11	370	15°	0,09
12	370	15°	0,13
13	370	35°	0,05
14	370	35°	0,09
15	370	35°	0,13
16	370	55°	0,05
17	370	55°	0,09
18	370	55°	0,13
19	430	15°	0,05
20	430	15°	0,09
21	430	15°	0,13
22	430	35°	0,05
23	430	35°	0,09
24	430	35°	0,13
25	430	55°	0,05
26	430	55°	0,09
27	430	55°	0,13

The values presented in the two tables above will be repeated for each type of surface, and the data centralization will be carried out in the most rigorous way.

6 CONCLUSIONS

After going through the stages of the design of experiments, according to the Taguchi method, we noticed that the use of this approach led to a significant reduction in the number of experiments required. Thus, instead of 270 tests for a single surface with one type of cutter, which would have generated a total of 2700 tests for all surfaces and both types of cutters, the number of tests was reduced to 27 for each type of cutter and a single surface, resulting in a total of 270 tests for all surfaces and both types of cutters.

Next, the experiments will be carried out according to the experiment plan, an aspect that gives special importance to each information obtained from the surface processing.

The input data will be used strictly according to the tables presented, thus giving the system increased rigidity and clarity. The experimental research will aim to determine the influence of process and technological parameters on surface quality, in the context of different types of surfaces and the diversity of tool types.

In order to ensure the achievement of these objectives, the optimal exploitation of the experimental dataset was achieved based on fundamental criteria, thus maximizing their usefulness.

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